Neutrino Oscillation Physics at the Deep Underground Science and Engineering Laboratory

Milind Diwan
Brookhaven National Laboratory

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Outline of talk

- **Description and status of the proposed Deep Underground Science and Engineering Laboratory (DUSEL).**
- **Physics of a Very Long Baseline Neutrino Oscillation Experiment.**
- **Status of VLBL experiment at Brookhaven National Laboratory.**

Opportunities for Long Term Collaboration.

http://int.phys.washington.edu/NUSEL

DUSEL History and Status

- 1965 Homestake mine excavates cavity for the clorine experiment for Ray Davis (BNL)
- Three decades of co-operation between mine company and scientists.
- Sep, 2000 company announces mine closure.
- By Fall 2000 Physics community in US saw an opportunity to have a world-class deep underground facility.
- Complex negotiations are taking place. The US-National Science Foundation has determined Homestake as the best site. (despite recent decision to turn off water pumps)

Science Underground

Identified by Bahcall committee

I. Solar Neutrinos

II. Double □ Decay

III. Dark Matter

IV. Nucleon Decay

V. Atmospheric □s

VI. Long Baseline □ Oscillation Expts.

VII. Supernova □s

VIII. Nuclear Astrophysics

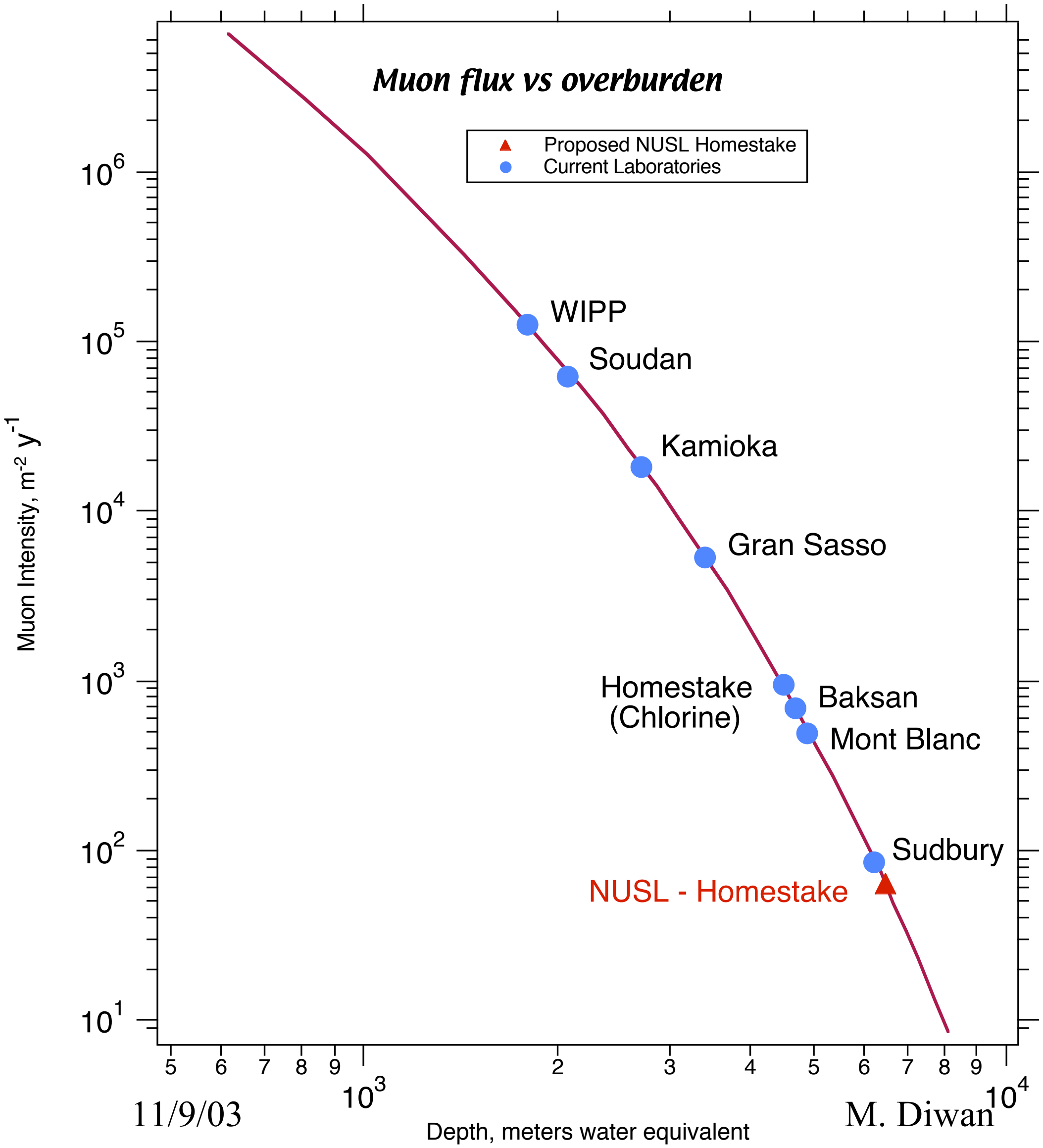
IX. Geoscience

X. Materials Dev. And Technology

XI. Microbiology

See: Underground Lab at http://www.sns.ias.edu/~jnb

Why go deep?



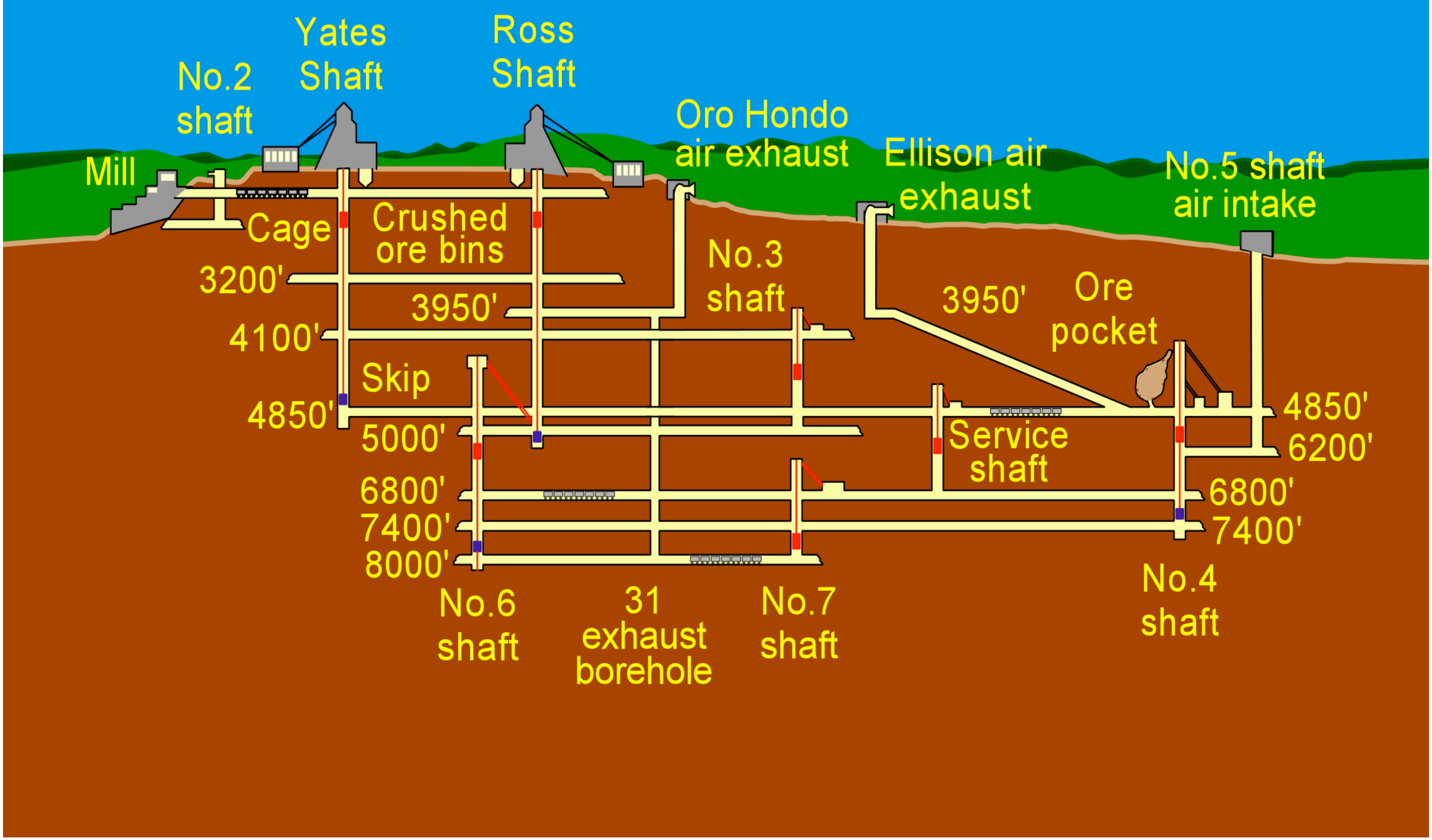
Many next generation experiments must be deep to achieve their ultimate sensitivity

- **SNO wouldn't have worked at Gran Sasso or Kamioka because of cosmogenic bkgs.**

SNO concern relevant to DM -- worry about potential neutron backgrounds with *no* accompanying muon signal

- **n's from Atm. ν NC reaction**
- **n's from μ induced photonuclear production in rock**
- **n's from μ DIS in rock**

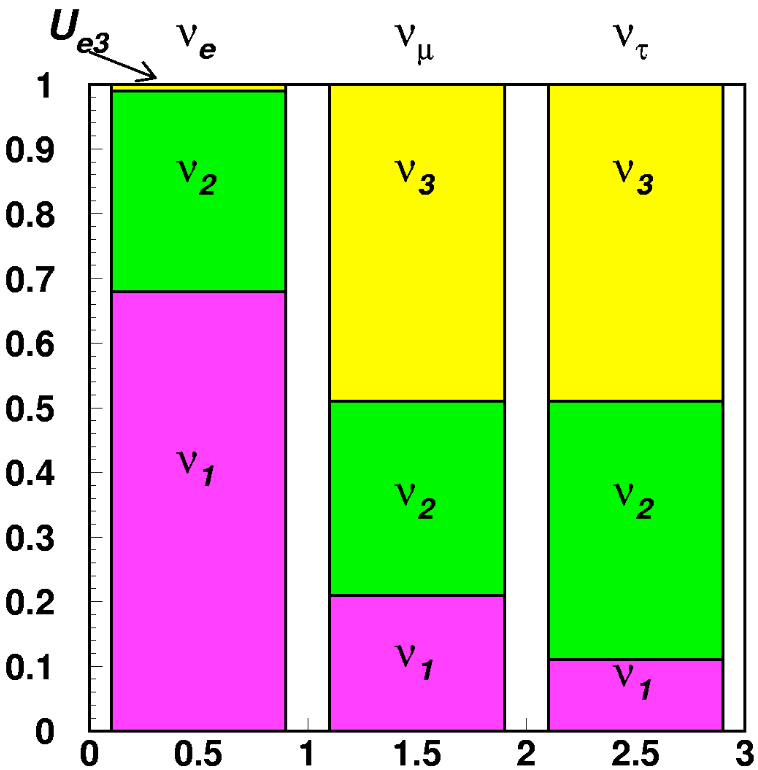
General Homestake Mine Development

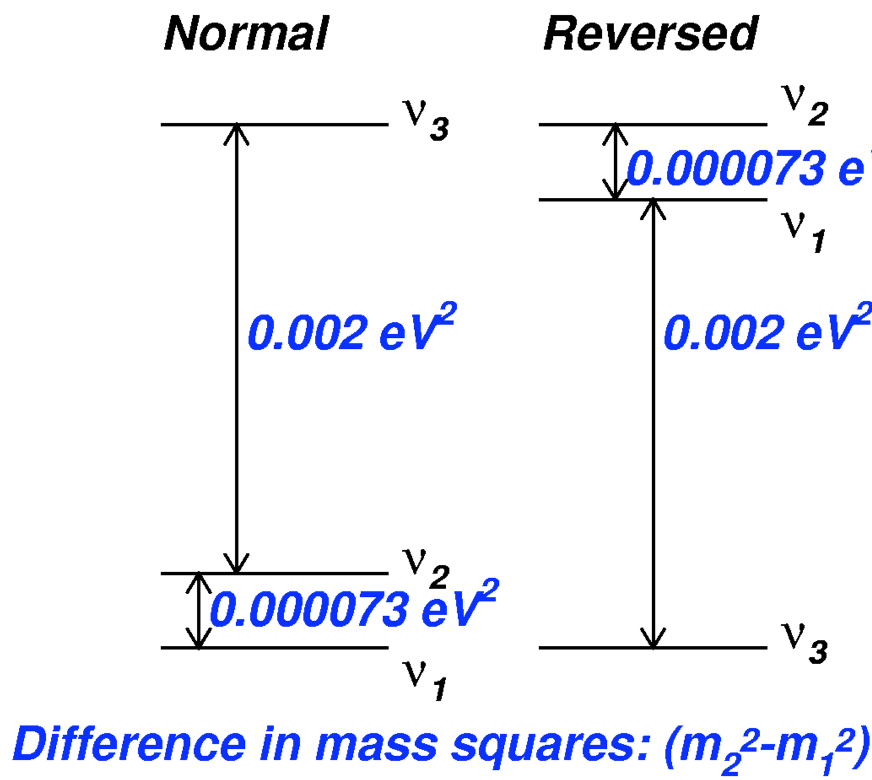


Very Long Baseline Neutrinos and the Next Generation Underground Detector

- A large detector of mass >500 kT natural extension of Super Kamiokande.
- Proposals: UNO, Hyper-Kamiokande, MMM different visions for achieving 1 MT.
- Very long baseline (>2000km) oscillation experiment to observe multiple oscillation nodes, natural next step in physics.
- Both classified as "Absolutely Central" in recent High Energy Physics future facilities panel.

Big goal: measurement of CP violation in leptons





Both mass differences important for observing Phase of Ue3. CP asym ~ L $\Delta m^2_{21}/E$

Physics Goals of the Very Long Baseline Neutrino Program

A plan to provide the following goals in a ***single facility***:

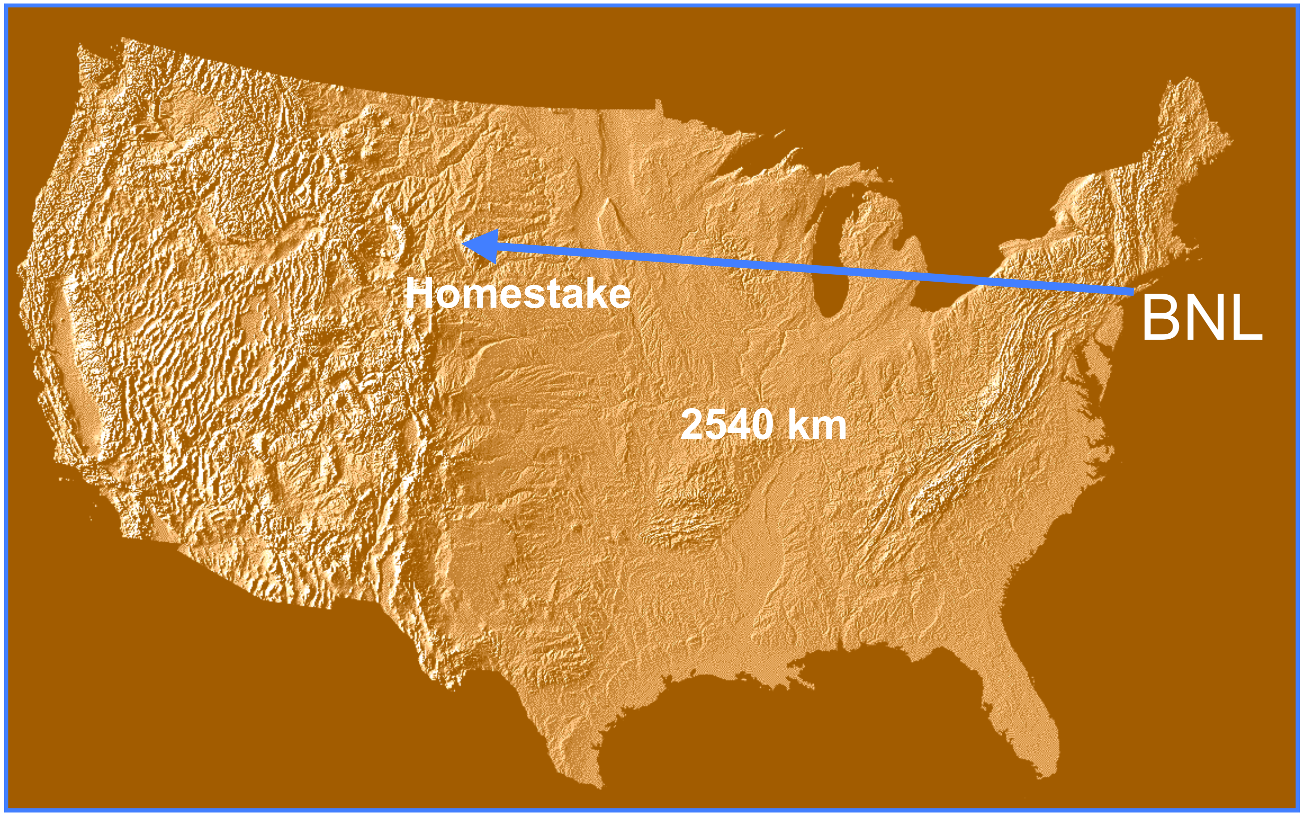
- precise determination of the oscillation parameters Δm_{32}^2 and $\sin^2 2\theta_{23}$

  Observation of oscillation nodes in the neutrino spectrum.

- detection of the oscillation of $\nu_\mu \to \nu_e$ and measurement of $\sin^2 2\theta_{13}$
- measurement of $\Delta m_{21}^2 \sin^2 2\theta_{12}$ in a $\nu_\mu \to \nu_e$ appearance mode, can be made if the value of θ_{13} is zero
- verification of matter enhancement and the sign of Δm_{32}^2
- determination of the CP-violation parameter δ_{CP} in the neutrino sector

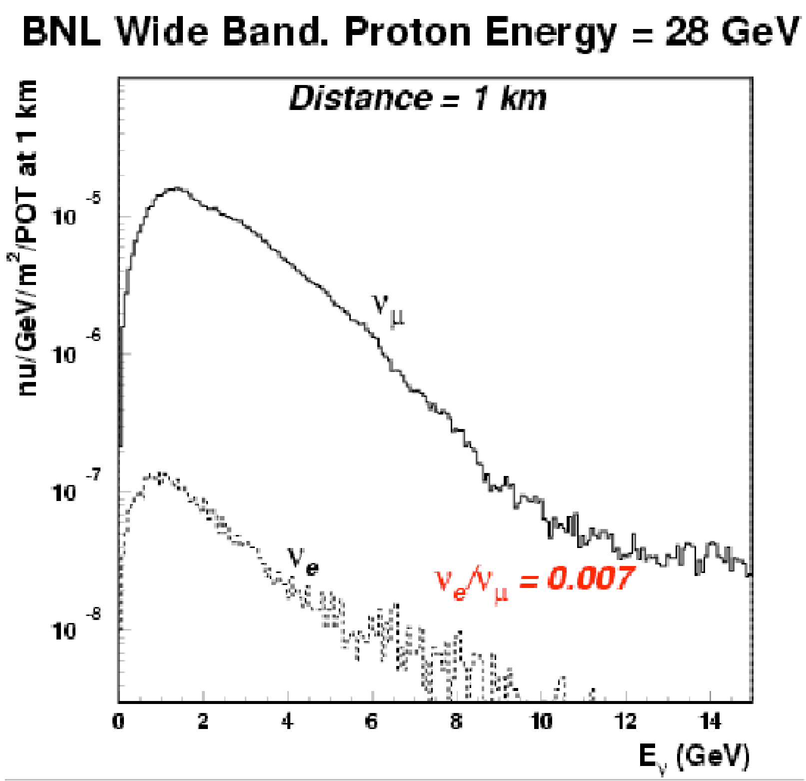
The use of a *single neutrino intense beam source* and *half-megaton neutrino detector* will optimize the efficiency and cost-effectiveness of a full program of neutrino measurements. If the value of $\sin^2 2\theta_{13}$ happens to be larger than ~0.01, then all the parameters, including CP-violation can be determined in the VLB program.

BNL Homestake 1 MW Neutrino Beam



28 GeV protons, 1 MW beam power
500 kT Water Cherenkov detector
5e7 sec of running, Conventional Horn based beam

Neutrino spectrum from AGS



- Proton energy 28 GeV
- 1 MW total power
- ~10^{14} proton per pulse
- Cycle 2.5 Hz
- Pulse width 2.5 mu-s
- Horn focused beam with graphite target
- $5\text{x}10^{-5}$ []/m^2/POT @ 1km
- 52000 CC events.
- 17000 NC events.

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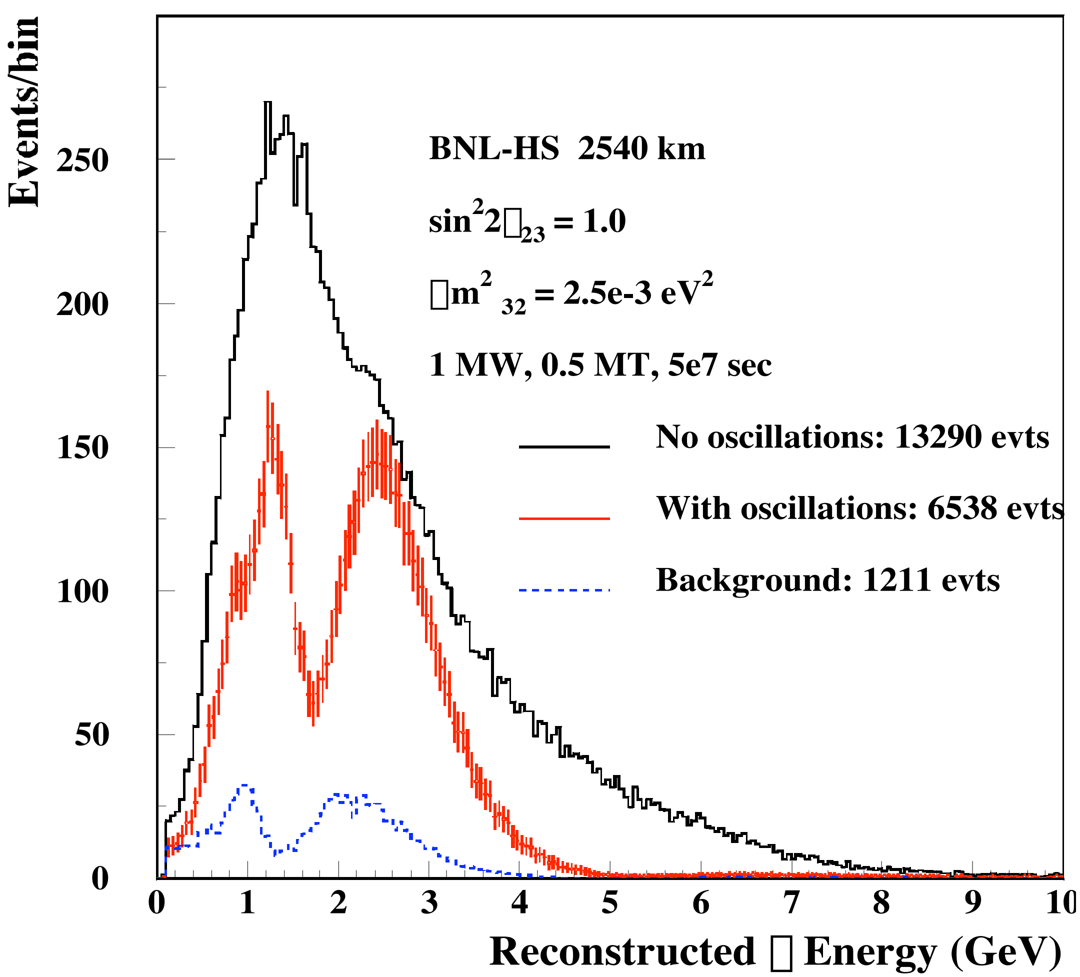
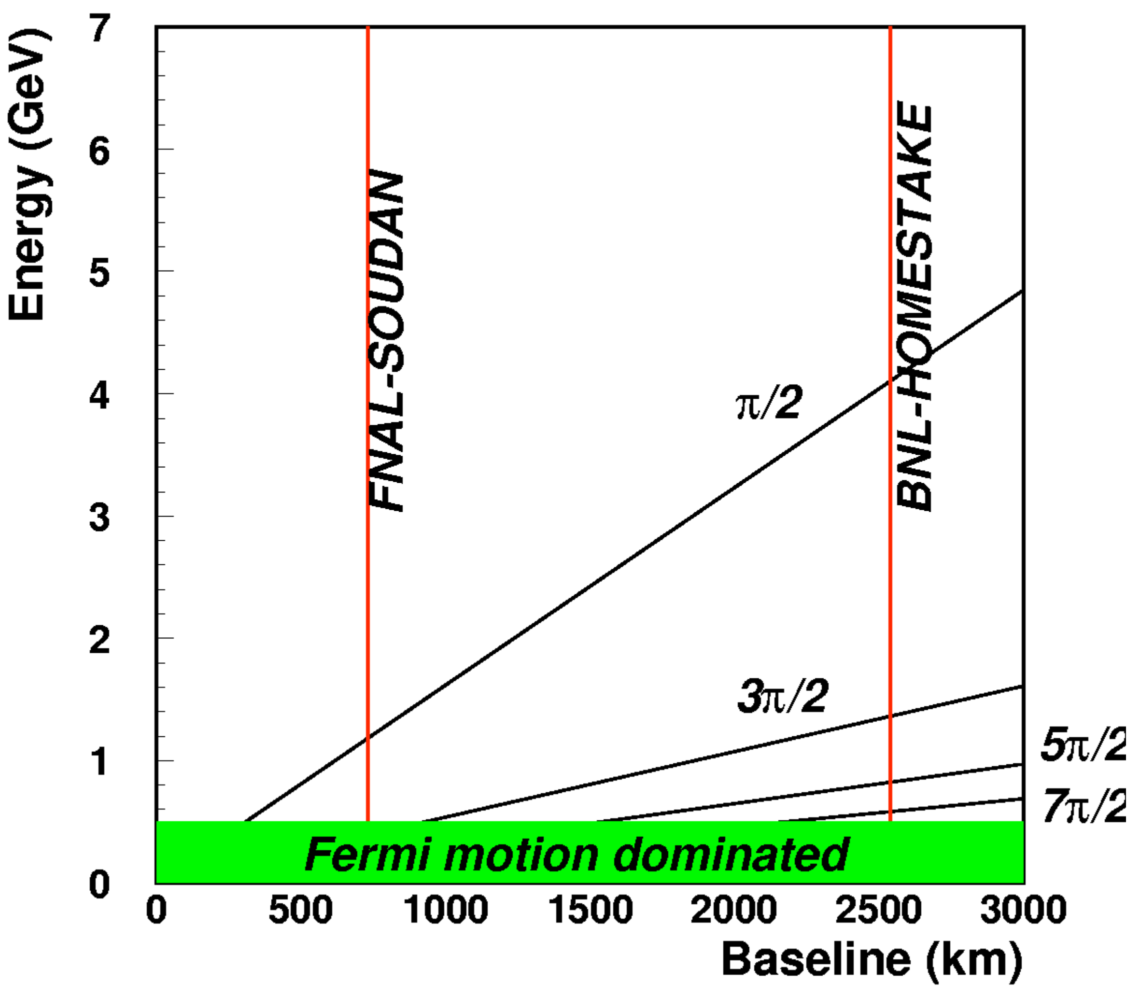
Advantages of a Very Long Baseline

ν_μ DISAPPEARANCE



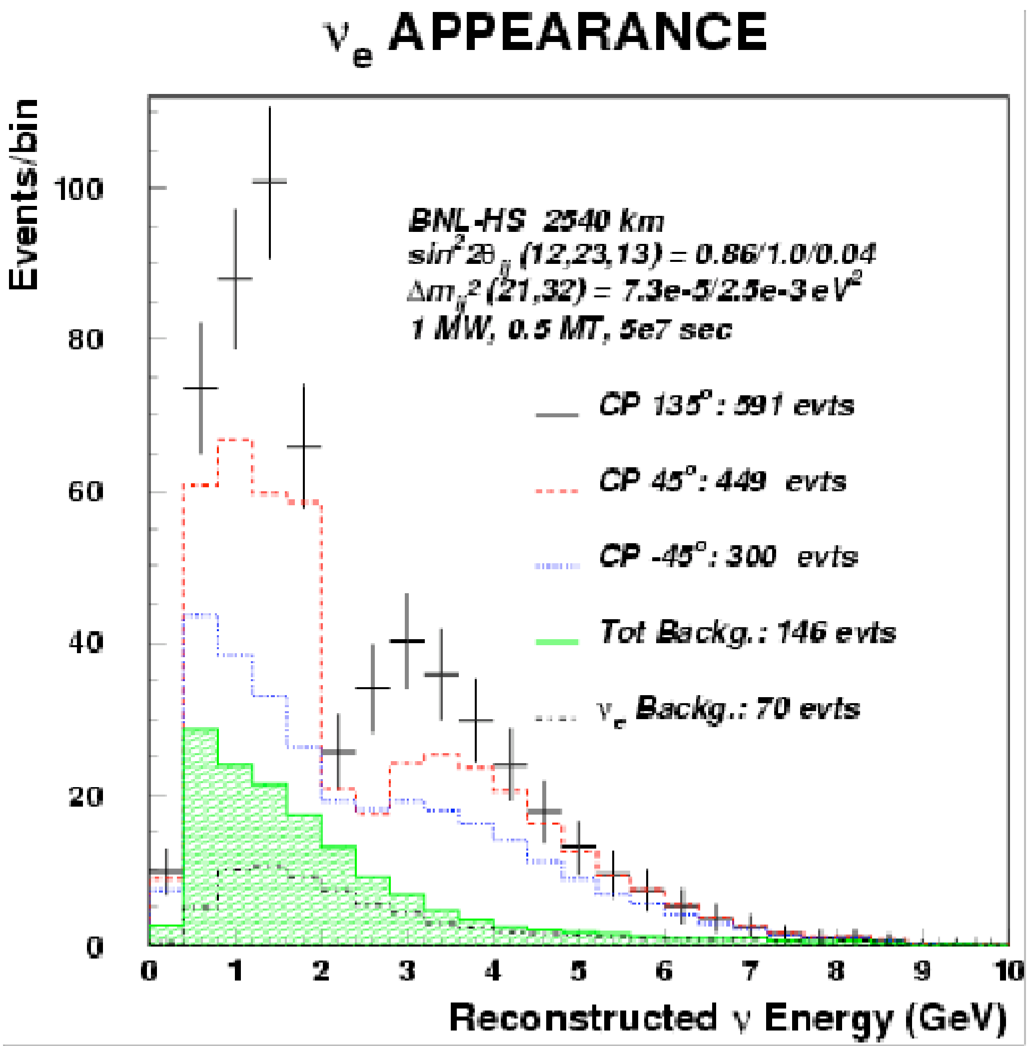
- neutrino oscillations result from the factor $\sin^2(\Delta m_{32}^2$ L / 4E) modulating the ν flux for each flavor (here ν_μ disappearance)
- the oscillation period is directly proportional to distance and inversely proportional to energy
- with a *very long baseline* actual oscillations are seen in the data as a function of energy
- the multiple-node structure of the very long baseline allows the Δm_{32}^2 to be precisely measured by a *wavelength* rather than an amplitude (reducing systematic errors)

Very Long Baseline Neutrino – Δm_{32}^2 Nodes



- neutrino node pattern is key to high-resolution Δm^2 measurements
- Fermi momentum sets E_ν>1 GeV/c to maintain ν energy resolution
- the distance scale is set by Δm_{23}^2
- BNL-HS 2540 km
- FNAL-HS 1290 km
- BNL-WIPP 2880 km
- BNL-Henderson 2770

ν_e Appearance Measurements

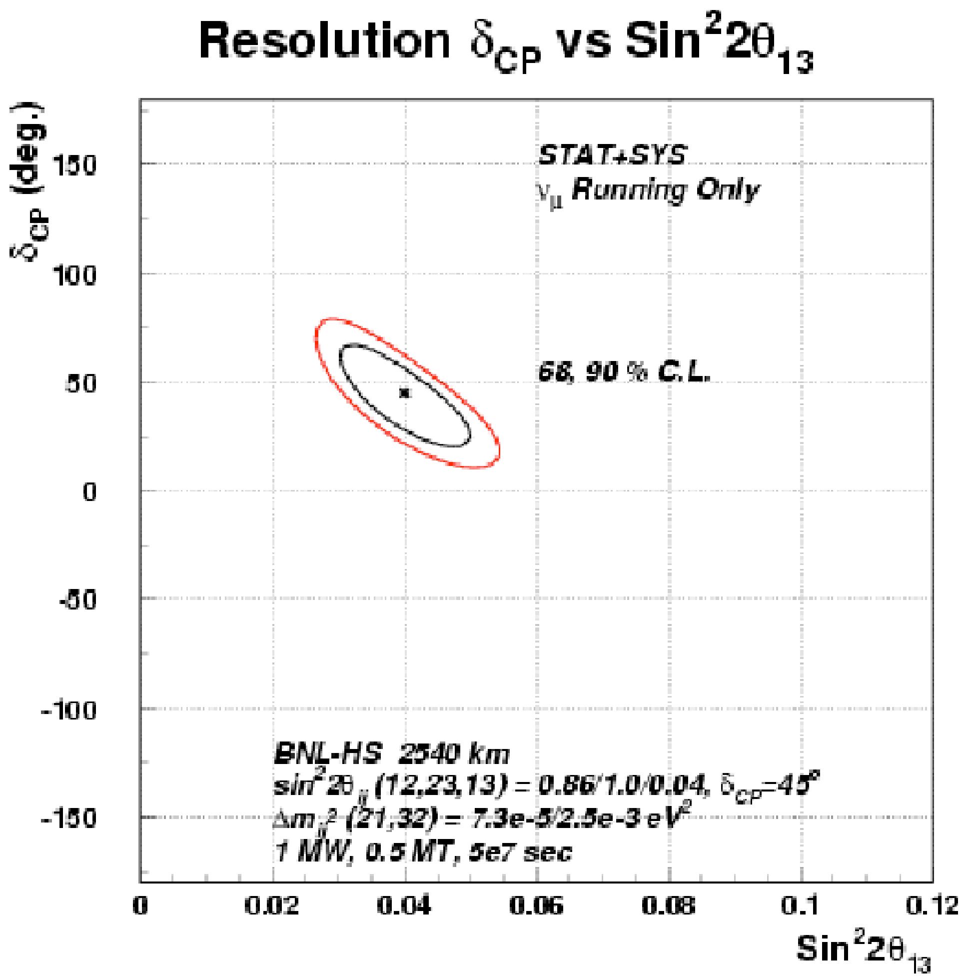


- a direct measurement of the appearance of $\nu_\mu \rightarrow \nu_e$ is important; the VLB method competes well with any proposed super beam concept
- for values > 0.01, a measurement of $\sin^2 2\theta_{13}$ can be made (the current experimental limit is 0.12)
- for most of the possible range of $\sin^2 2\theta_{13}$, a good measurement of θ_{13} and the CP-violation parameter δ_{CP} can be made by the VLB

3 somewhat overlapping regions:

- Matter dominated >3 GeV
- CP dominated 1-3 GeV
- Δm^2_{21} dominated <1.5 geV

Mass -ordering and CP-violation Parameter δ_{CP}



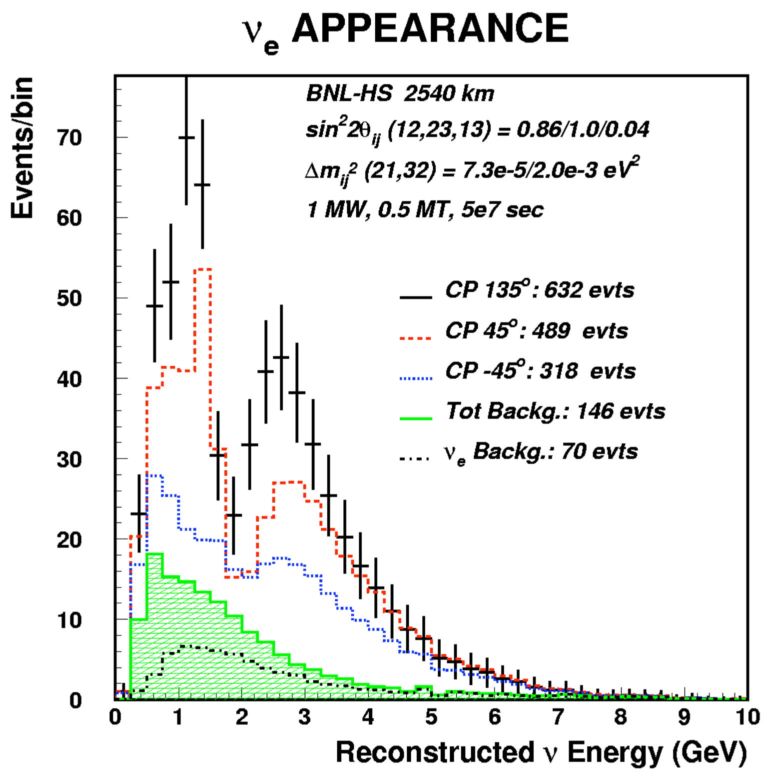
- the CP-violation parameter δ_{CP} can be measured in the VLB exp. And is relatively insensitive to the value of $\sin^2 2\theta_{13}$
- the mass-ordering of the neutrinos is determined in the VLB exp; $m_1 < m_2 < m_3$ is the natural order but $m_1 < m_3 < m_2$ is still possible experimentally; VLB determines this, using the effects of matter on the higher-energy neutrinos

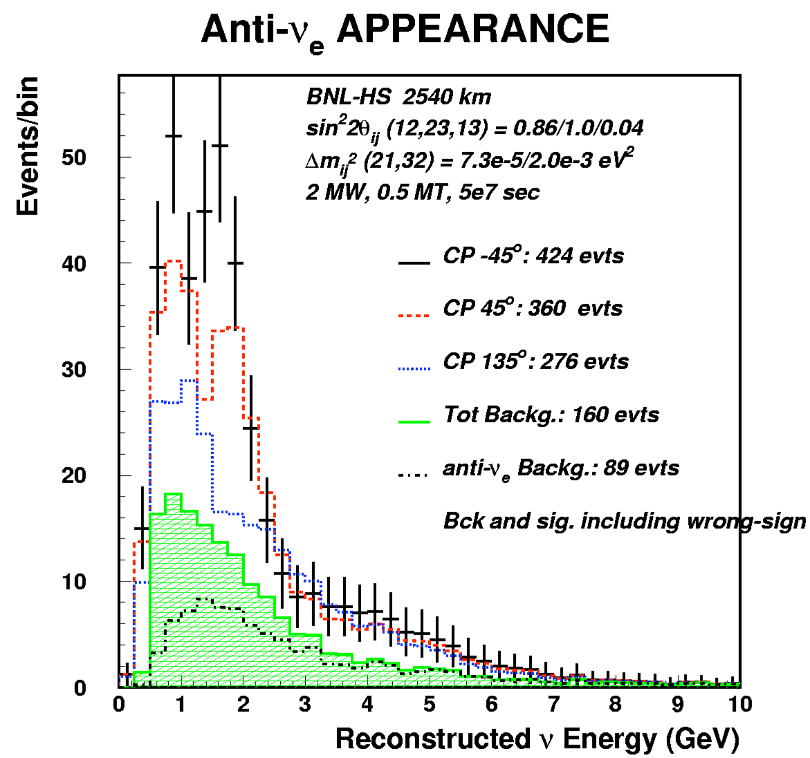
Only Neutrino data is needed for this Plot

Use fit to 3 regions spectrum to extract parameters

Neutrino vs. Anti-neutrino

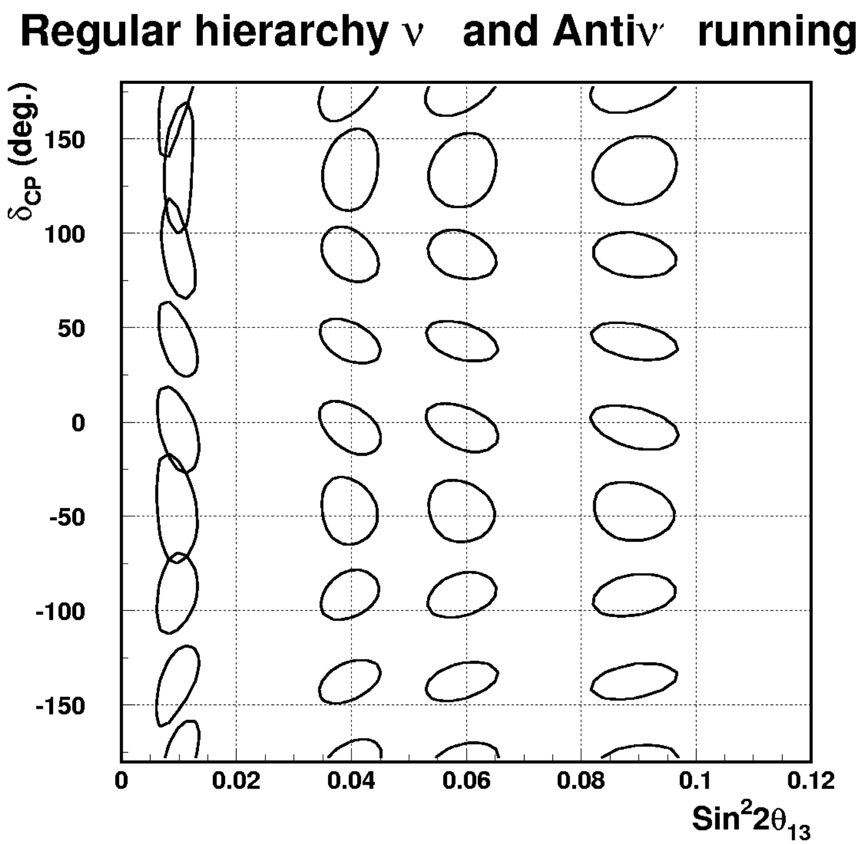
Regular mass ordering





- High energy. Need 2 MW for anti-nu to get same stats
- Spectra get exchanged for reversed mass ordering !

Important Considerations

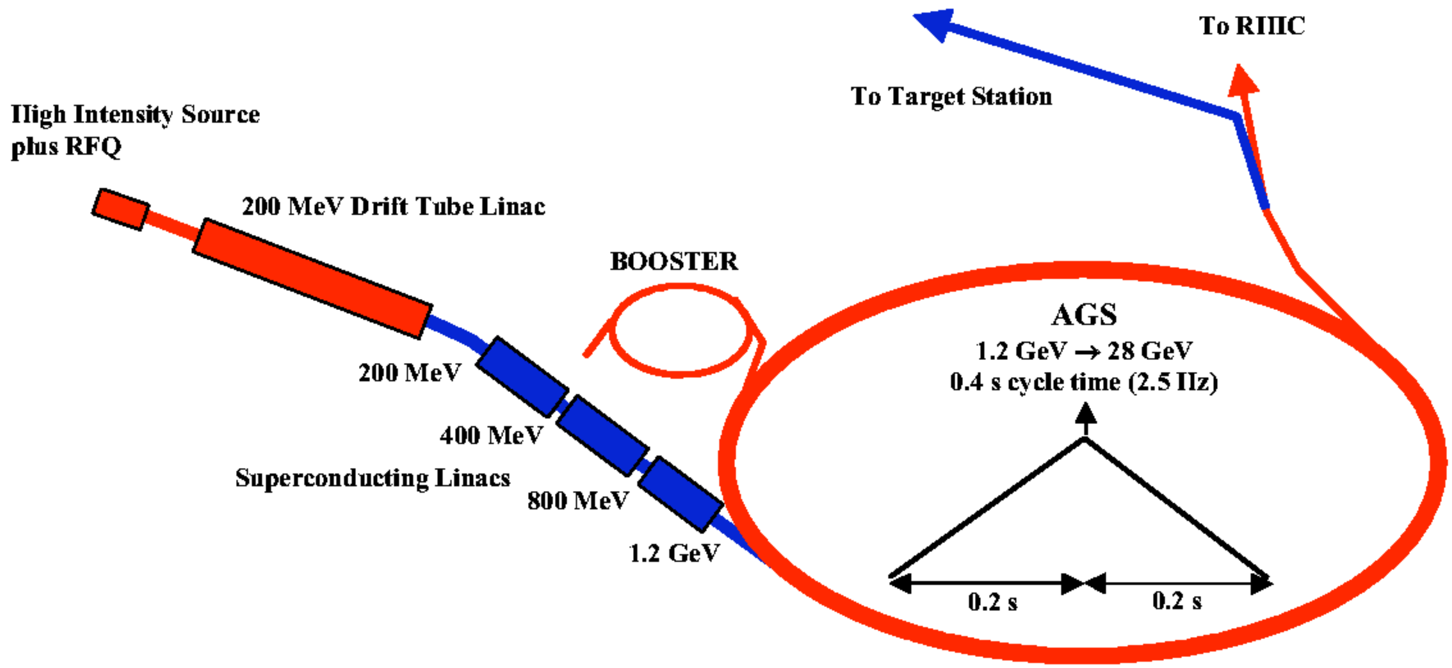


If signal is well above background CP resolution is indep. of $\sin^2 2\theta_{13}$

Wide band beam and 2540 km eliminate many parameter correlations.

For 3-generation mixing only neutrino running is needed. Anti-neutrino running gives better precision or New physics.

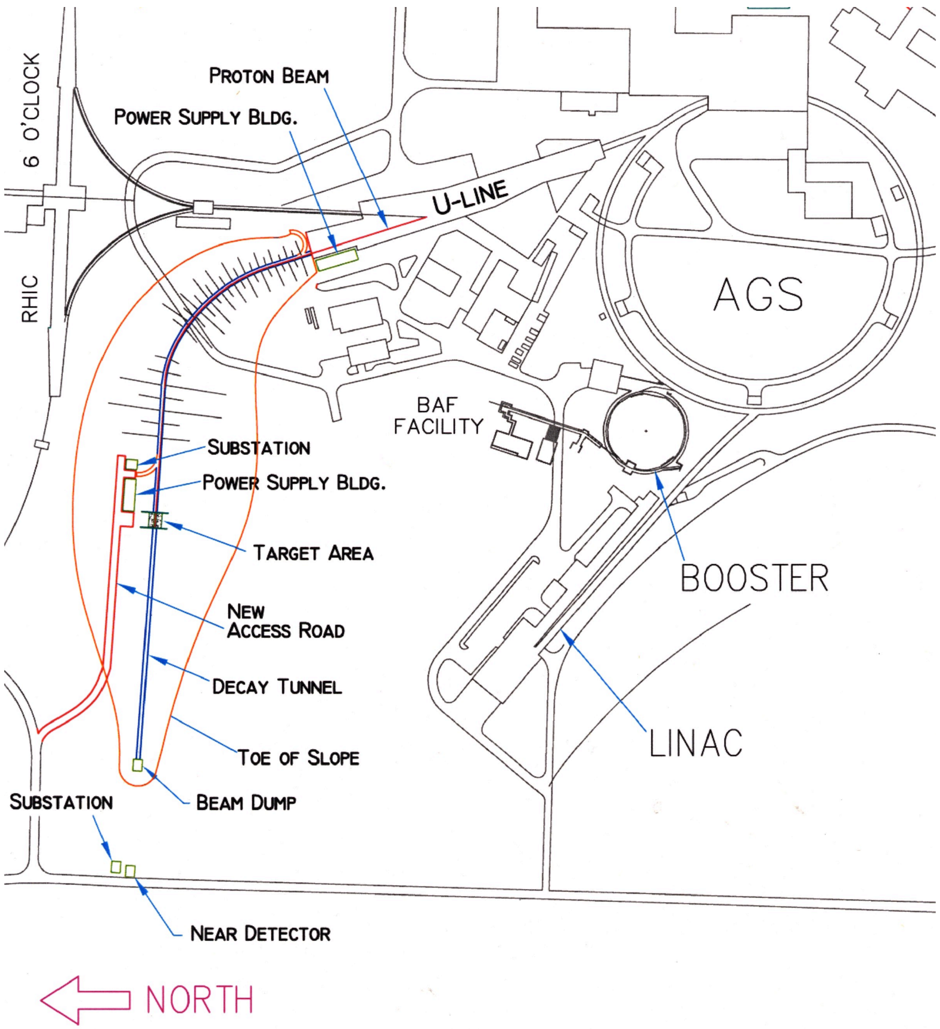
BNL-AGS Target Power Upgrade to 1 MW



AGS is currently the highest intensity machine.
Simple plan. Run the AGS faster. 2.5 Hz
Need new LINAC @ 1.2 GeV to provide protons.
Cost $265M FY03 (TEC) dollars.
Energy is 28 GeV. 2.5 Hz operation is 1 MW

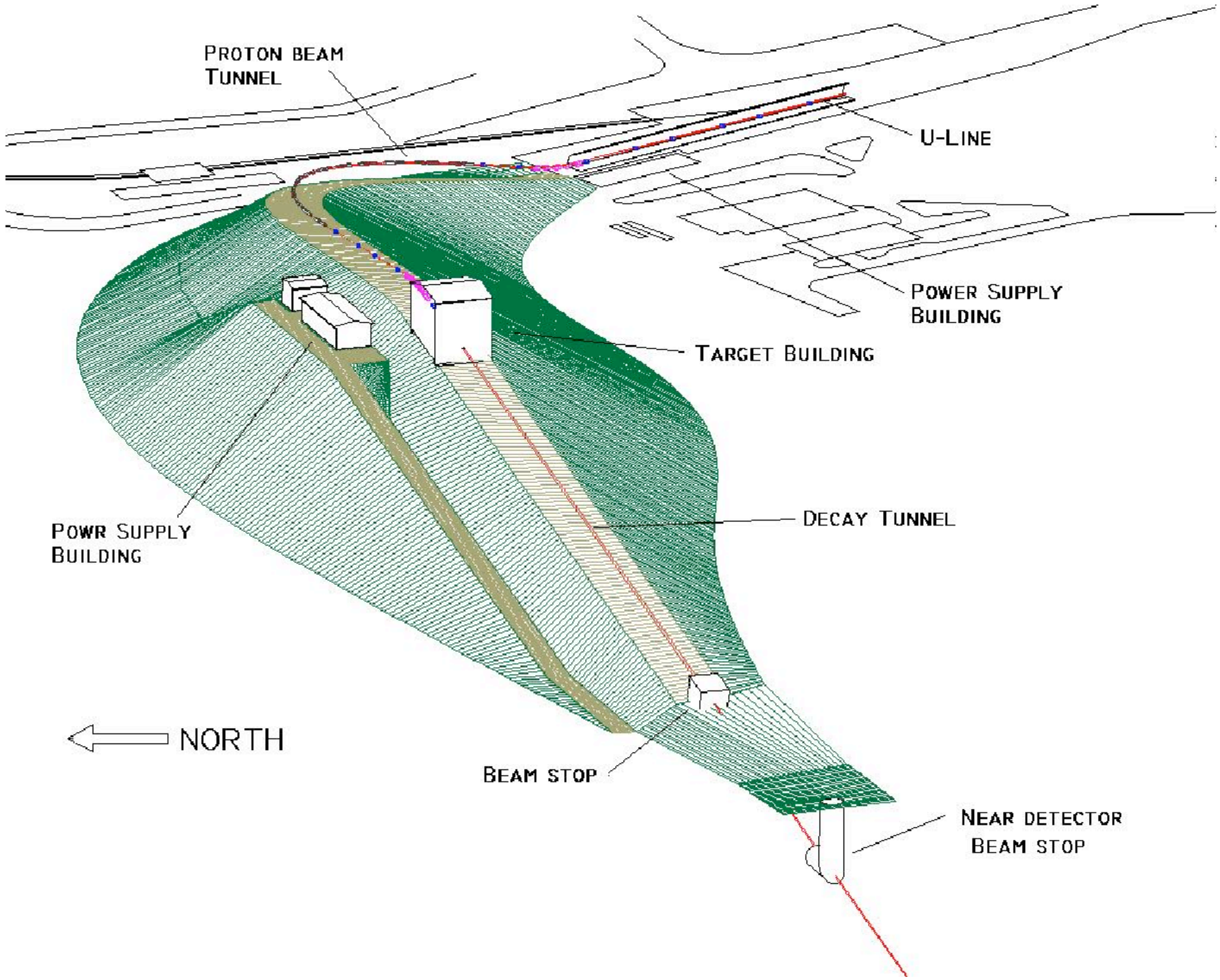
$$7 \times 10^{13} protons/2sec$$
$$9 \times 10^{13} protons/0.4sec$$

Super Neutrino Beam Geographical Layout



- BNL can provide a *1 MW capable Super Neutrino Beam*
- the neutrino beam can aim at any site in the western U.S.; the Homestake Mine is shown here
- there will be no environmental issues if the beam is produced atop the hill illustrated here and the beam dumped well above the local water table
- construction of the Super Neutrino Beam is essentially de-coupled from AGS and RHIC operations

3-D Neutrino Super Beam Perspective



Detector

- Requirements: Very ambitious !
  - 500 kTons fiducial mass for both Proton decay and neutrino astro-physics and neutrino beam physics.
  - ~10 % energy resolution on quasielastic events
  - Muon/electron discrimination at <1%
  - 1, 2, 3 track event separation
  - Showering NC event rejection at factor of ~15
  - Low threshold (~10-15 MeV) for supernova search
  - Part of the detector could have lower threshold for solar neutrino detection.
  - Time resolution of ~few ns for pattern recognition and background reduction.

Detector choices

- Liquid Argon TPC
  - May not need 500 kT
  - 100 kT module never been built. Too large a step from current 300ton.
  - Needs detailed simulations to make sure there are no hidden pitfalls, but should perform adequately.
- Water Cherenkov
  - 50 kT SuperK is existence proof.
  - Current understanding of background rejection: need another factor of 3 to 5 in the 1-2 GeV range.
  - Could additional imaging capability help? (Aquarich concept by Ypsilantis)

Conclusions

GOAL: Fore-front facility for deep underground and neutrino science.
Many common areas with INO

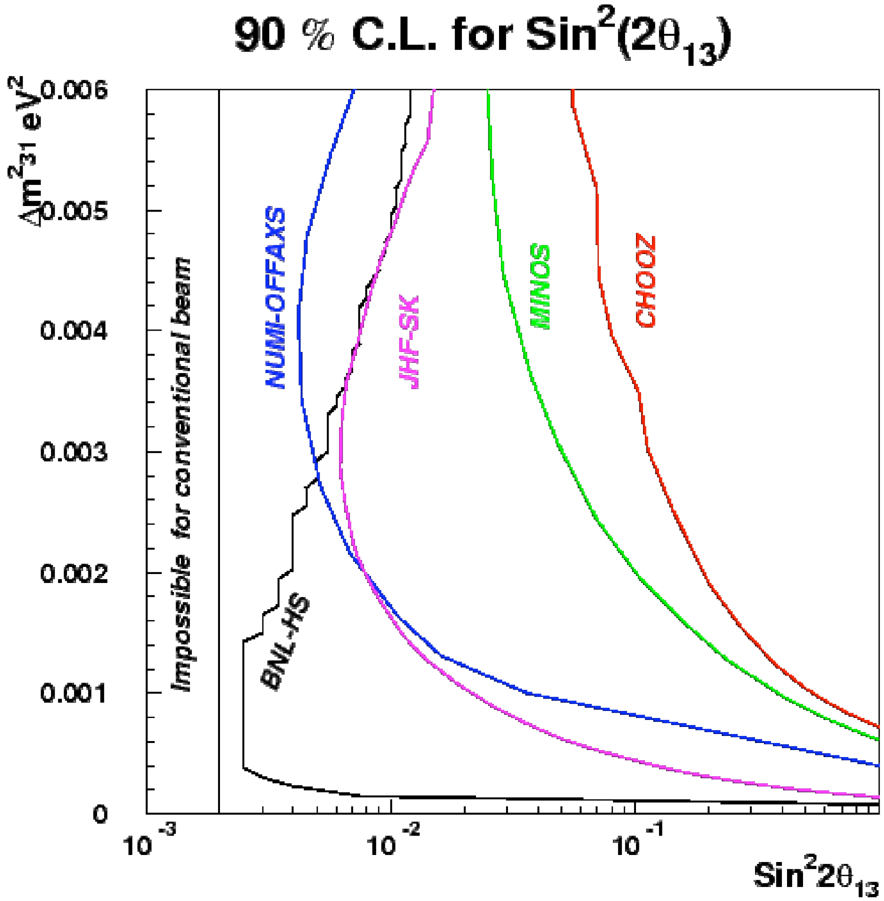
- **Deep Underground Science and Engineering Laboratory (DUSEL) is in consideration in the US. Current selected (by National Science Foundation) site is the Homestake mine in Lead, South Dakota.**

  There are other possible sites. The VLB physics reach is approximately same for 2000 to 4000 km.

  The *Very Long Baseline* method, utilizing a *1 MW Super Neutrino Beam* from BNL's AGS, coupled with a *half-megaton water Cerenkov detector* in the Homestake Mine in Lead, SD, offers a uniquely effective plan.

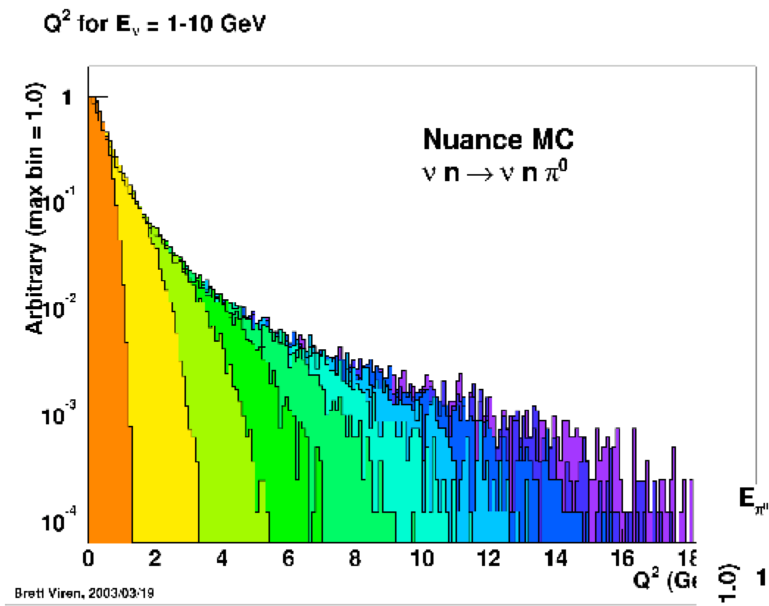
- **Work continues to understand the best detector design.**
  - **Workshop at UCLA Dec 3-5 http://physics.ucla.edu/hep/proton**
- **Detector has applications far beyond neutrino oscillations.**
- **A deep underground 500 kT detector with the described performance characteristics will be a unique facility for Physics.**

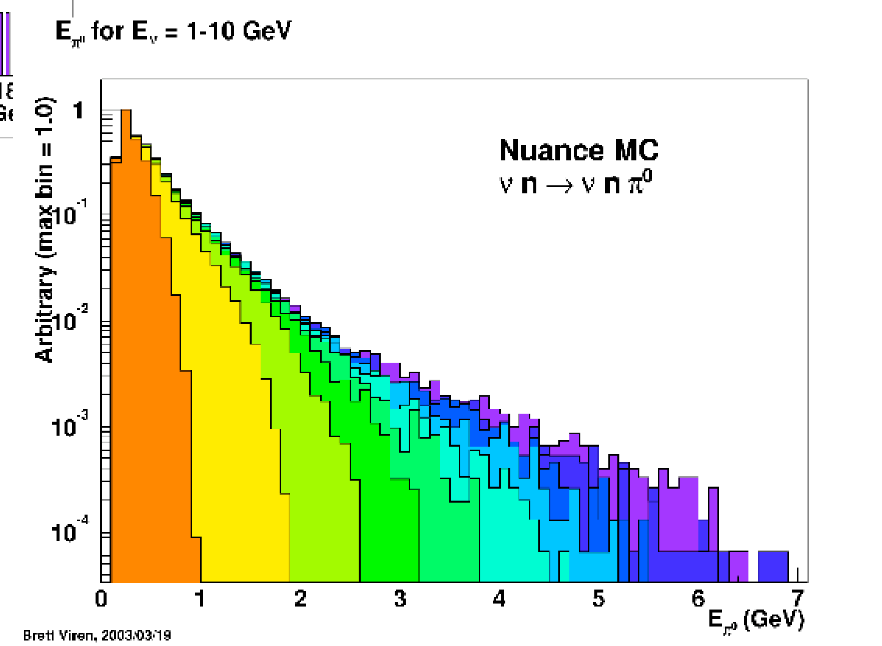
Comparisons to other projects



- BNL-HS has reach to lower Dm2 and a larger physics agenda.
- No conventional beam experiments can beat the background from beam contamination
- Plot ignores CP, multi-node, matter effects

NC events have a shape that falls in Q2 and visible energy regardless of neutrino energy.





A 1-4 GeV neutrino beam and 2500 km ideal because background is naturally low at 3 GeV peak.

AGS 1 MW Upgrade and SC Linac Parameters

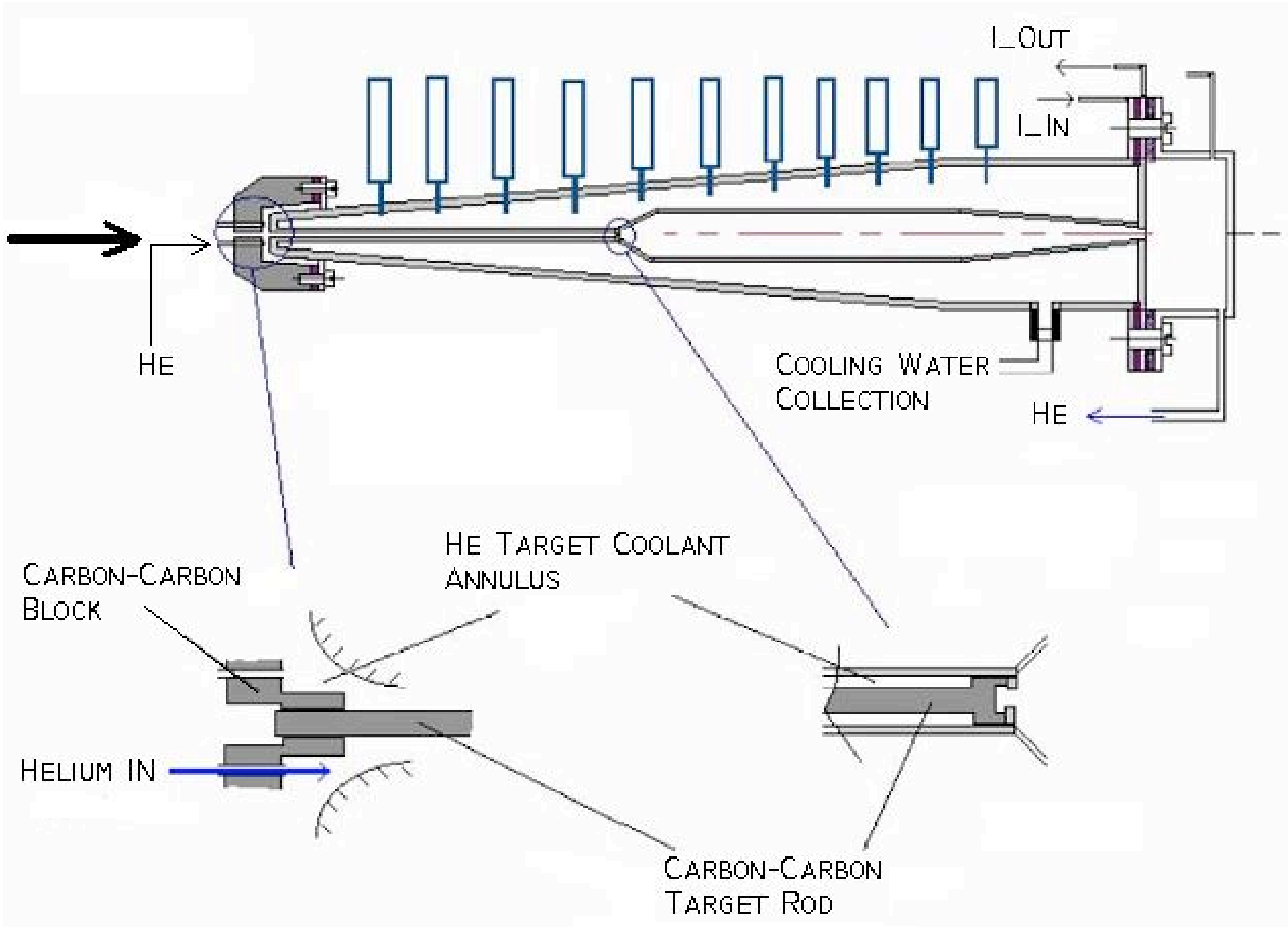
Proton Driver Parameters

Item	Value
Total beam power	1 MW
Protons per bunch	0.4×10^{13}
Beam energy	28 GeV
Injection turns	230
Average beam current	38 mA
Repetition rate	2.5 Hz
Cycle time	400 ms
Pulse length	0.72 ms
Number of protons per fill	9.6×10^{13}
Chopping rate	0.75
Number of bunches per fill	24
Linac average/peak current	20/30 mA

Superconducting Linac Parameters

Linac Section	LE	ME	HE
Av Beam Pwr, kW	7.14	14.0	14.0
Av Beam Curr, mA	35.7	35.7	35.7
K.E. Gain, MeV	200	400	400
Frequency, MHz	805	1610	1610
Total Length, m	37.82	41.40	38.32
Accel Grad, MeV/m	10.8	23.5	23.4
norm rms □, □ mm-mr	2.0	2.0	2.0

1 MW Target for AGS Super Neutrino Beam



- 1.0 MW He gas-cooled, Carbon-Carbon target for the Super Neutrino Beam